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This report, the first in a series on the STEAMER project, describes an initial framework for the development of techniques to automatically generate explanations of the operation of physical devices like those found in propulsion plants.

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PROJECT STEAMER: I. TAXONOMY FOR GENERATING EXPLANATIONS OF HOW TO OPERATE COMPLEX PHYSICAL DEVICES

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PROJECT STEAMER: I. TAXONOMY FOR GENERATING EXPLANATIONS OF HOW TO OPERATE COMPLEX PHYSICAL DEVICES

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FOREWORD

This research and development was conducted under contract #N00123-81-D0794 with Bolt Beranek and Newman, Inc. in support of Navy Decision Coordinating Paper Z1177-PN (Advanced Computer-Aided Instruction), subproject Z1177-PN.03 (STEAMER: Advanced Computer-Based Training for Propulsion and Problem Solving). It was sponsored by the Chief of Naval Operations (OP-01). The main objective of the STEAMER effort is to develop and evaluate advanced knowledge-based techniques for use in low-cost portable training systems. The project is focused on propulsion engineering as a domain in which to investigate these computer-based training techniques.

This report, the first in a series on the STEAMER project, describes an initial framework for the development of techniques to automatically generate explanations of the operation of physical devices like those found in propulsion plants. Intended users of this report are system maintainers and other research personnel.

The contracting officer's technical representative was Dr. James Hollan.

JAMES F. KELLY, JR.
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SUMMARY

Problem

The main objective of the STEAMER effort is to develop and evaluate advanced knowledge-based techniques for use in low-cost portable training systems. The project is focused on propulsion engineering as a domain in which to investigate these computer-based training techniques. Mastering the operation of a propulsion plant requires a deep understanding of how and why it functions as it does.

Objective

The objective of the effort described herein was to find a way to effectively communicate the understanding necessary to operate complex systems like propulsion plants.

Approach

Textual materials directed at providing students with an understanding of how complex devices operate were examined.

Results

The examination revealed a diversity of explanations. Thus, a taxonomy for organizing explanations of physical devices was presented. Also, evidence for the taxonomy was provided, along with examples from current Navy engineering texts and operations manuals.

Conclusions

This taxonomy appears useful as a way of organizing work on automatically generating explanations as part of an intelligent computer-aided instruction system. It provides a way of focusing future work on different types of explanations and a possible framework for evaluating the effectiveness of different types of explanations. The automatic generation of one particular type of explanation, the physical-causal type, has already been accomplished.

CONTENTS

INTRODUCTION

Problem

The STEAMER project is an attempt to develop an advanced computer-aided instruction system for teaching the operation of Navy propulsion plants. Mastering the operation of a propulsion plant requires a thorough understanding of how and why it functions as it does. This understanding provides the mental structure that supports the recall and execution of previously learned procedures and the construction of procedures to deal with novel situations. Trainees require a large amount of information and knowledge before they can understand the operation of a propulsion plant. Currently, they acquire much of their knowledge through the study of engineering texts and procedures and operations manuals.

Objective and Approach

The objective of this report was to find a way to effectively communicate the understanding necessary to operate complex systems like propulsion plants. To meet this objective, textual materials directed at providing students with an understanding of how complex devices operate were examined.

RESULTS

Examination of text materials directed at providing students with an understanding of important subsystems reveals diverse types of explanations. These explanations appear to differ in level of detail, conceptual perspective, degree of "match" with physical reality, and degree of "quantitativeness." This is not surprising. The explanations found in current training materials are generated by experienced technicians and engineers, serve many different purposes, and evolve through use. Because no explicit theory of explanation exists, it is not known how to produce optimal explanations for given situations. The different types, therefore, reflect their history rather than any coherent pedagogical structure. However, it is likely that the implicit knowledge used to generate these explanations includes a tacit theory of explanation.

The rest of this section describes the results of the analysis of traditional training materials aimed at making explicit some of the tacit guidelines that skilled writers of training materials use to generate explanations. First, an initial taxonomy of explanations is presented. Examples from current training texts and engineering manuals are provided as evidence supporting this taxonomy. Next, a set of basic distinctions that appear to underlie the explanation types and how these distinctions lead to a space of explanation types is discussed. Finally, some implications of the taxonomy for the design of intelligent computer-aided instruction systems are highlighted.

Taxonomy of Explanations

The first step was to examine Navy training and operations manuals, select a large set of explanations, and categorize them in what seemed a natural way. There are nine different types of explanations in this initial taxonomy. Each is described in turn.

Behavioral Explanation

A *behavioral explanation* of a *system* is one of the simplest types. It describes the overall behavior of a system with respect to its inputs and outputs and ignores internal structure. Behavioral accounts are often used as ingredient explanations for physical-causal accounts, another type to be discussed. An important part of the behavioral explanation is a description of the limits of its applicability. These limits are usually given in terms of the boundary conditions within which the described behavior is expected to hold.

An example of a behavioral explanation is the following description of a reducing valve:

> A reducing valve can be set for any desired discharge pressure, within the design limits of the valve. After the valve has been set, the reduced pressure will be maintained regardless of changes in the supply pressure (as long as the supply pressure is at least as high as the desired delivery pressure) and regardless of the amount of reduced pressure fluid that is used. (Bureau of Naval Personnel, 1970, p. 378)

This explanation describes the overall behavior of the system (maintaining desired discharge pressure) and the limits between which that behavior holds (the design limits and supply pressure as high as the desired pressure).

Physical-Causal Explanations

A physical-causal explanation typically views the system as a causal chain. Each link of the chain consists of a local device that passes an effect on to the next link (deKleer, 1979). There may exist complicated explanations of these devices (the operation of local devices may themselves be complex). With respect to the superordinate system, however, they are viewed from a behavioral standpoint.

The physical-causal explanation is a convenient fiction. It breaks up an essentially continuous system into a discrete set of temporally ordered events with causal linkages between them. The events often do not exist in the temporal form described, and the causal flow is often opposite to the direction of physical force. The causal flow is constrained by the connectivity of the ingredient devices to flow only through a small set of well-defined "conduits."

Explanations with a physical-causal perspective are action-oriented. Terms such as "push," "pull," and "force" are common. These words are often used to describe changes in state such as physical location, pressure, and temperature. These changes are freely intermixed, provided there is a local device that can be used to pass one along to another via a legal conduit.

The following is an example of such an explanation for a particular type of device, a pilot valve. This particular valve has an air inlet to a chamber at its top separated by a diaphragm from a spring. The diaphragm is attached to a stem that projects down through the spring and bears against a valve.

> If the controlled pressure increases, the upper diaphragm is depressed and the stem moves downwards. The pilot valve opens, admitting additional control air to the seal supply regulator valve actuator. . . .

> If the controlled pressure decreases, the adjusting spring raises the upper diaphragm and stem. This raises the nozzle disc from its seat on the nozzle, and operating air pressure is vented. (Naval Sea Systems Command, 1978, p. 10-12)

Within the domain examined, a large percentage of the explanations are physical-causal in nature. This is interesting because these descriptions not only omit a large amount of information, but they typically impose an event structure on the operation of the system that does not actually exist. In the pilot valve, unlike the description of successive discrete events, successive snapshots would show that the entire system had adjusted a small amount between each one. The event structure of the physical causal explanation would result if we focussed on one part, advanced time, moved to another part while rolling back time, then advanced time again.

Synchronous Explanation

The physical causal explanation is a convenient fiction that operates on a level removed from the continuous fine-gained changes that actually occur in physical systems. When it is necessary to understand these finer-grained structures, a synchronous account is used. Synchronous explanations aggregate the aspects of physical processes that do not change over time.

An example of a synchronous explanation is:

> The position of the diaphragm at any given moment is determined by the relative strength of two opposing forces: (1) The downward force exerted by the adjusting spring, and (2) the upward force exerted on the underside of the diaphragm by the reduced pressure steam. These two forces are continually seeking to reach a state of balance. (Bureau of Naval Personnel, 1970, p. 378-379)

Information Flow

The classic example of an information-flow based explanation is a feedback system. Substances and devices are described as carriers of information. Instead of describing forces balancing, the forces are described as comparison operations; instead of describing pressure changes in one chamber causing a corresponding pressure change in another, the connecting line is described as sensing a pressure change in one chamber and transmitting that information to another.

There are strong parallels between the information flow perspective and the physical causal one. These parallels undoubtedly derive from our strong notion that information can only be transmitted as a physical effect. Thus, the channels of information flow are the channels of causal flow. However, the parsing of the componential structure may be different. Several devices in the physical-causal description may end up as one device in the information flow description or a single physical-causal device may be split across devices of the information flow explanation.

Explanations based on an information flow perspective use such terms as sense, compare, and actuate. An example for a fuel oil unloading valve is:

> The actuator line, which is installed in the fuel oil service pump discharge line, senses the pump discharge pressure. Pressure variations in the pump discharge line actuate the bourdon tube in the Masoneiland Air Pilot Controller. Through a system of adjustable linkage located with the instrument case, a corresponding air signal is sent to the diaphragm section of the valve. . . ." (Naval Sea Systems Command, 1978, p. 9-24)

State-Attribute Explanations

The primary purpose of many physical systems is to move some substance around and change its attributes or state. In a propulsion plant, the substance can be fuel oil, water, energy, brine, distillate, lube oil, etc. The point of view that emphasizes the substance and changes in its attributes is called the state-attribute explanation. This type of explanation is often used to provide motivation for many of the design principles and operating procedures that operators must learn. Because steam is often under high pressure, containing pipes must be seamless and valves should never be left partially open.

Fundamental to the human conception of substance is that it is conserved. What goes in comes out, somewhere. This simple fact gives this formulation enormous inferential power. Understanding level changes in a water tank or energy losses in a system are examples that depend on this type of explanation.

Devices are seen as agents that effect changes of attributes of substances. A condenser changes fluid in vapor state to liquid state. It is the same substance, just in a different state. A heat exchanger lowers the temperature of fluid going through the hot leg.

Two examples of state-attribute explanations are:

> . . . some of the sea water in the first-effect shell is boiled and vaporized by the supply steam. The remaining portion becomes more dense and has a higher salinity than the original sea water feed; . . . (Bureau of Naval Personnel, 1970, p. 459)

> Feedwater from the main feed booster pump discharge enters the first stage of the main feed pump and the pressure is boosted by the centrifugal action of the first stage impeller. The feedwater then enters the second and third stages, where the pressure is further increased. Finally, the feedwater enters the fourth stage where the main feed pressure reaches the desired pressure that will feed the boiler, maintaining 75 psi differential through the feedwater control valve. (Naval Sea Systems Command, 1978, p. 5-38)

Transport-Medium

Another distinct explanation type that is used in explaining numerous situations is the transport-medium explanation. In fact, the most global view of a propulsion plant relies on this model. The primary substance to be moved is energy; the transport medium is water:

> On steam-driven ships, steam serves the vital purpose of carrying energy to the engines. The source of this energy may be the combustion of a conventional fuel oil or the fission of a radioactive material. In either case, the steam that is generated is the medium by which thermal energy is carried to the ship's engines,. . . (Bureau of Naval Personnel, 1970, p. 157)

This approach does have more generality than explaining energy transport in a water medium. Explanations of distilling plants with water carrying salt, air ejectors with steam carrying noncondensable gases, and even tube walls carrying heat in a heat exchanger are examples of the usefulness of the transport-medium viewpoint.

Component Explanations

A component explanation is a simple one. It describes the component devices of a system.

For example:

> The basic components of a saturated-steam boiler are merely the tubes in which steam is generated, the drums and headers in which water is contained and steam is collected, and the furnace in which combustion takes place. (Bureau of Naval Personnel, 1970, p. 230)

An example of a more specific system (a spring-loaded reducing valve) is:

> The principle parts of the valve are: (1) the main valve, an upward-seating valve which has a piston on top of its valve stem; (2) an upward seating auxiliary or controlling valve; (3) a controlling diaphragm; and (4) an adjusting spring. (Bureau of Naval Personnel, 1970, p. 378)

The basic component explanation can be augmented with descriptions of relative importance of subparts and can in general have a multilevel hierarchical structure with subparts broken into subsubparts.

Topological Explanations

Topological explanations add information about the connectivity of the components in a component explanation. Thus, a component account is a necessary prerequisite for a topological one. The topological explanation provides the connectivity information necessary for the determination of device interactions described by physical-causal and information flow approaches.

Topological explanations are often communicated with diagrams such as circuit schematics or piping diagrams. However, manuals frequently include verbal descriptions as well. An example is:

> The steam for the 1200-psig desuperheated and reduced steam system is supplied from the desuperheater outlet of each boiler through a globe stop valve . . . A guarding valve, manually operated at the valve, is also installed in the outlet. . . . After the guarding valve, the piping from each boiler is led to that boiler's two forced draft blowers . . . (Naval Sea Systems Command, 1978, p. 3-6)

Geometric Explanations

A geometric explanation adds quantitative information to a topological model. A geometric explanation of a system or component is typically communicated using scaled diagrams, engineering drawings, cutaway diagrams, or photographs. Verbal descriptions of system geometry are often found in manuals. They include selected aspects of the information that is typically contained in an accompanying diagram. An example of such a verbal description communicating parts of a geometric perspective is:

> The water drum, located at the lower end of the generating bank tubes, is 24 inches inside diameter, 2-11/32 inches thick. The tube sheet and the wrapper sheet are the same thickness. Both drum heads are semi-ellipsoidal. The front drum head is fitted with a 12 by 16-inch elliptical manhole with hinged cover. (Naval Sea Systems Command, 1978, p. 1-22)

The Basic Distinctions

The taxonomy just described is an unstructured list of different types of explanations. It is believed that these types are really samples from a more structured space defined by a set of basic distinctions. These distinctions capture fundamental differences in the physical explanation types examined and may, in fact, be fundamental to the way people think about complex physical systems. The four distinctions described below are the most obvious.

Structure vs. Mechanism

In explaining a physical device, one can talk about how it is put together and one can talk about how it functions.

A structural explanation of a device emphasizes its spatial qualities. It can describe the component structure, connectivity, or geometric structure of the device. Time varying properties are excluded: a structural explanation is a static one. It is often communicated using schematic diagrams, engineering drawings, or photographs.

An explanation of a device as a mechanism emphasizes the time varying properties of it. The explanation will be action-oriented and include such terms as "pushes," "moves," "causes," and "actuates." Whatever the objects described in a mechanistic explanation, the explanation emphasizes behavior; it explains what the device does.

Individuated vs. Aggregate Events/Components

In explaining a device, one can talk about specific individual components and their spatial relationships, or about specific individual events and their temporal and causal relationships.

If either the events of a mechanistic explanation or the components of a structural explanation are similar to each other, one can discuss them in the aggregate, talking about a prototypical event or component or using statistical concepts such as average properties and behaviors. The aggregate model of a device is extremely useful if large numbers of similar events or objects are responsible for producing some behavior. For example, discussing the Bernoulli effect in terms of the pressure and velocity of an individual molecule at a given time would be useless. On the other hand, explaining the effect by describing an aggregate of molecules with different pressure/velocity components to their motion makes it obvious that a nozzle must effectively filter high-velocity, low-pressure molecules through it.

The following example from a Navy engineering text effectively utilizes aggregate events to produce a synchronous explanation.

> When heat is transferred to a liquid, the average velocity of the molecules is increased and the amount of internal kinetic energy stored in the liquid is increased. As the average velocity of the molecules increases, some molecules which are at or near the surface of the liquid momentarily achieve unusually high velocities; and some of these escape from the liquid and enter the space above, where they exist in the vapor state. As more and more of the molecules escape and come into the vapor state, the probability increases that some of the vapor molecules will momentarily have unusually low velocities; these molecules will be captured by the liquid. As a result of this exchange between the liquid and the vapor, a condition of equilibrium is reached and an equilibrium pressure is established. (Bureau of Naval Personnel, 1970, p. 183)

Qualitative vs. Quantitative

The distinction between qualitative and quantitative explanations is complex. Many relationships and properties of objects can be conveyed in a very qualitative manner. For example, the following physical-causal explanation of a two-piston hydraulic system makes no mention of quantities or even changes in quantities. It talks solely about pressures being transmitted, forces causing pressures, and vice versa.

> You push down on the brake pedal and force the piston in the master cylinder against the fluid in that cylinder. This push sets up a pressure on the fluid just as your finger does on shaving cream in a tube. The pressure on the fluid in the master cylinder is transmitted through the lines to the brake cylinders in each wheel. This fluid under pressure pushes against the pistons in each of the brake cylinders and forces the brake shoes out against the drums. (Bureau of Naval Personnel, 1971, p. 62)

An example of a quantitative refinement of the force and pressure relationships in a two-piston hydraulic system is illustrated by the following:

> If two pistons are used in a hydraulic system, the force acting on each will be directly proportional to its area and the magnitude of each force will be the product of the pressure and the area. (Bureau of Naval Personnel, 1970, p. 394)

This explanation makes specific reference to the quantifiable characteristics of force, pressure, and area and presents the quantitative relationships that hold among them.

External vs. Internal Properties

The remaining distinction is between explanations that focus on the internal properties of a device versus those that describe only the external properties. Externally-based explanations are concerned with the behavior of the system as a function of its inputs and outputs. These explanations discuss variations in input parameters and their consequent effect on output, treating the system as a black box and ignoring internal functioning. Another approach to dynamic device explanations is to trace the internal processes of a specific device. Here the emphasis is on the operation of lower level components as a function of local variations in pressure, temperature, velocity, and state of the substance flowing through the device.

The distinction between internal and external structure enables flexibility in the amount of detail included in an explanation. Rather than describing a device in terms of its lowest level components, one can talk about it as a set of interacting subdevices, each of which is described only in terms of its external properties.

Objectification

One of the distinctions among explanations that is evident but harder to generalize comes from the choice of what to objectify. Some explanations focus on concrete entities like valves, springs, or superheated steam. Others focus on abstract entities like information, energy, and physical effect.

It is suspected that the choice of what to objectify is determined to a large extent by the degree to which powerful inference techniques can be applied. A tendency is to try to portray a system in terms of some "object" or substance that moves around the system. For example, focusing on the notion of energy in explaining the operation of a steam plant allows a unified explanation of its operation, in which energy is described as starting locked in the oil in chemical form, being converted in the boiler to thermal form, and finally transferred to the turbines where it is converted to mechanical form. By talking about the uniform notion of energy, extremely powerful inference techniques, based on the conservation laws, can be applied. If one talked about the changing attributes of the oil, water, steam, and the turbine, the power to make these inferences and hence unify the understanding would not be available.

Dimensionalized Space of Explanations

The distinctions described, when considered together, essentially dimensionalize the space of explanation types. Thus, it is possible to place each of the explanation types in the taxonomy into specific regions in this dimensionalized space. The component and topological explanations are structural, for they describe the static, spatial qualities of devices. They both focus on internal individuated features of devices and describe these features in qualitative terms. The geometric explanation is also structural, internal, and individuated. However, elements in a geometric explanation are conveyed in quantitative terms and thus differ from the other two on this dimension.

The six remaining explanations in the taxonomy can be considered to fall on the mechanism side of the structure-mechanism dimension. They each emphasize action, behavior, and time-varying properties of devices. The physical-causal and information flow explanations describe internal, qualitative, individuated processes occurring within a device or subsystem. While the synchronous explanation shares an internal, qualitative focus with the former two, it discusses the events in the aggregate. The behavioral explanation presented is also qualitative and aggregate, but external.

Both the transport-medium and state-attribute explanations are internal, qualitative, and individuated models of mechanism. They differ from the information-flow and physical-causal explanations in what they objectify. The transport-medium explanation objectifies some amount of substance embedded in a medium; the state-attribute explanation objectifies subtance moving through a device. The physical casual explanation objectifies the abstract notion of "physical effect" while information-flow objectifies the abstract notion of "information."

If these dimensions are valid, then it should be possible to fill in the empty cells with corresponding explanations. For example, the brake-pedal explanation in the discussion of the qualitative-quantitative distinction is an example of a mechanistic, external, quantitative, aggregate model. An example of a structural, internal, qualitative, aggregate model can be simply generated: A heat exchanger described as a large collection of parallel tubes.

Efforts have not yet been attempted at filling out the space with examples of each type of explanation but, rather, have focussed so far on using the existing taxonomy to select and generate explanations as part of the developing STEAMER system. The main purpose of this report is to lay out the distinctions as a framework for examining explanations. Work is continuing on the examination of explanations and on the usefulness of the distinctions presented here.

Implications for CAI

The dimensionalized space of explanations presented in this report provides a potential framework for selecting and generating explanations for use in intelligent CAI systems. Using this classification system, one can begin to assess which type of explanation is likely to be most useful in a given situation. For example, techniques to generate automatically physical-causal explanations of complex devices have been developed (Forbus & Stevens, 1981). When used to explain the operation of a reducing valve, a simple control device, this explanation is very natural in that it describes the reducing valve as a set of locally interacting causal events. However, this alone will not always provide an explanation that is completely satisfying. When the reducing-valve explanation was used in pilot instruction, people felt it did not deal with the continuous behavior of the device. A synchronous explanation, provided by the experimenter, that focused on the aggregate temporal behavior of the device completed the description of the reducing valve in a natural way.

The fact that two explanations were needed, and that the taxonomy was able to furnish one that complemented the already existing one, is evidence that the taxonomy is useful for selecting and generating explanations of how complex systems work. One imagines being able to say: "To describe a reducing valve, use one physical-causal explanation at the level of the first set of subcomponents, and one behavioral; but to describe a venturi, use one aggregate explanation objectifying individual molecular events, and one state-attribute with energy objectified."

The reason for the necessity of more than one type of explanation, it is believed, arises because people typically reason about complex systems using multiple mental models. There is a growing body of evidence for this (Stevens & Collins, 1980; Gentner, Gentner, & Collins, 1981; Williams, Hollan, & Stevens, 1981), and one should thus expect that multiple explanations of complex system operation would be necessary. It is possible that these different types of explanations exist precisely because several different types of mental models are used to reason about complex physical systems. These multiple mental models each provide ways of making different sets of inferences easily and quickly. Thus, to reason about the failure of a control valve to adjust as load changes, one would use a physical-causal mental model and note paths in the causal sequence that would result in failure. But to reason about poor efficiency in a heat exchanger, one might use a synchronous model aggregated across heat-exchange events to look for clogged tubes.

If this view is correct, then the proper goal of instruction is to determine what models are necessary to reason in the ways useful to perform the tasks associated with a given system and then communicate explanations embodying those models.

CONCLUSIONS

This taxonomy is probably incomplete and requires empirical evaluation before it can be used as a serious tool in any form of curriculum development, whether computer-based or not. In its present state, it provides a basis for focusing efforts in intelligent CAI system development on small parts of the problem of teaching how complex devices operate. Further research is necessary to determine whether certain types of explanations are more effective than others, how multiple explanations should be coordinated to provide the understanding necessary to operate complex equipment, and how to generate and present these explanations using intelligent CAI technology.

In its role as providing an effective focussing mechanism, the taxonomy has already enbled the STEAMER project to develop effective methods for generating physical-causal explanations (Forbus & Stevens, in press).

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